

Emerging trends in neuromodulation for schizophrenia: a global bibliometric analysis

Nurfaizatul Aisyah Ab Aziz ^{1#}, Siti Atiyah Ali ^{1#}, Nor Asyikin Fadzil ², Zamzuri Idris ^{3,4} and Sabarisah Hashim ^{3,4*}

¹ Faculty of Cognitive Sciences and Human Development, Universiti Malaysia Sarawak, Sarawak, Malaysia

² Psychiatry Department, School of Medical Sciences, Universiti Sains Malaysia, Kelantan, Malaysia

³ Department of Neurosciences, School of Medical Sciences, Universiti Sains Malaysia, Kelantan, Malaysia

⁴ Brain and Behaviour Cluster, School of Medical Sciences, Universiti Sains Malaysia, Kelantan, Malaysia

Co-first authors

* Correspondence: rissha@usm.my; Tel.: +609-767-6374

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Abstract: The utilization of neuromodulation techniques is increasingly capturing the attention of researchers and clinicians as potential non-pharmaceutical interventions for treating schizophrenia, especially among drug-resistant schizophrenia patients. Assessing the existing landscape of research activity and identifying gaps in neuromodulation-schizophrenia research is crucial for strategic planning and guiding future research in this domain. This bibliometric analysis paper aims to discern the publications and research trends in neuromodulation schizophrenia studies spanning 2019 to 2023. The Scopus database search was performed using the related keywords. Neuromodulation-schizophrenia-related publications were retrieved from the Scopus database from 2019 to 2023. Bibliometric analyses were performed using Harzing's Publish or Perish, Microsoft Excel and VOS viewer software programs. Three hundred fifty-three publications from the Scopus database were retrieved and analyzed to answer the research questions. The highest number of publications, 87, was observed in 2022. The United States led the way in publishing neuromodulation schizophrenia research with 96 articles. Keyword analysis revealed that "transcranial direct current stimulation" (tDCS) and "transcranial magnetic stimulation" (TMS) were the most prevalent neuromodulation techniques investigated in schizophrenia research. Transcranial-focused ultrasound (TUS) emerged as a novel and current neuromodulation technique explored in treating schizophrenia, as indicated by the analysis of selected journal articles. This bibliometric paper provides insights into the current status, knowledge base, and future directions of neuromodulation-schizophrenia studies, which will serve future researchers in focusing on applying neuromodulation techniques as potential non-pharmaceutical interventions for schizophrenia.

Keywords: Neuromodulation; Schizophrenia; Neurostimulation; Non-pharmaceutical treatment; Bibliometric

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1.0 INTRODUCTION

Schizophrenia is a chronic and disabling neurological disorder. The World Health Organization (WHO) estimates that approximately 24 million individuals worldwide – or one in every 300 people (0.32%) are affected by schizophrenia ([WHO, 2022](#)). It results in psychosis and is linked to serious impairment. Numerous aspects of life are impacted by this impairment, including social, familial, professional, educational, and personal functioning ([WHO, 2022](#)).

There are quite a few treatment options for schizophrenia, which include pharmaceutical and non-pharmaceutical treatments. Pharmaceutical treatments, such as the usage of second-generation antipsychotic (SGA) drugs, are the agents of choice for the first-line treatment of schizophrenia. However, adverse effects such as weight gain, hyperlipidemia, and diabetes mellitus can contribute to the increased risk of cardiovascular mortality observed in schizophrenia patients ([Chiliza et al., 2015](#); [Patel et al., 2014](#); [Raedler, 2010](#)). Furthermore, tardive Dyskinesia (TD), a severe, abnormal involuntary movement disorder, is a common comorbidity in schizophrenia patients due to long-term exposure to antipsychotic drugs ([Uludag et al., 2021](#)). This could also result in an increase in nonadherence rates among them. Meanwhile, some patients are drug-resistant and thus require non-pharmaceutical treatments.

Non-pharmaceutical treatments include the usage of neuromodulation. Neuromodulation is a fast-expanding field of study encompassing a broad range of implantable and non-invasive technology-based techniques for treating neurological and neuropsychiatric disorders ([Johnson et al., 2013](#); [Krames et al., 2009](#)). It is the process of interacting with and intervening with the neurological system using electrical, electromagnetic, pharmacological, or optogenetic methods with the purpose of long-term activation, inhibition, alteration, and/or regulation of neuronal activity ([Johnson et al., 2013](#); [Krames et al., 2009](#)).

For example, the non-invasive neuromodulation therapy induced by neurofeedback training (NFT) using electroencephalography (EEG), magnetoencephalography (MEG), or functional magnetic resonance imaging (fMRI) can train the brain activity to enhance cognitive-motor abilities that disrupted due to neurological or neuropsychological disorders ([Grosselin et al., 2021](#); [Okazaki et al., 2015](#); [Sorger et al., 2019](#)).

Meanwhile, transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) are the neuromodulation strategies that involve the delivery of magnetic or electrical current, respectively, through probes positioned at the scalp of the head ([Hamani & Moro, 2012](#)). The stimulation sites depend on the symptoms of the patients, intending to specifically influence the cognitive, emotional, and behavioral aspects of the patients. Invasive neuromodulation strategy includes deep brain stimulation (DBS). The DBS requires surgical intervention to implant electrodes ([Luo et al., 2021](#)).

The usage of neuromodulation therapy has proven to have good prognosis with other neurological and neuropsychiatric disorders such as depression ([Akhtar et al., 2016](#); [Bloom et al., 2023](#); [Downar & Daskalakis, 2013](#)), Alzheimer's ([Chang et al., 2018](#); [Luo et al., 2021](#)), Parkinson ([Schuepbach et al., 2013](#); [Yuan et al., 2020](#)), stroke ([Ting et al., 2021](#); [Yin et al., 2020](#)), obsessive-compulsive disorder (OCD) ([Bergfeld et al., 2021](#); [Zhou & Fang, 2022](#)), attention deficit hyperactivity disorder (ADHD) ([Okazaki et al., 2015](#); [Wong & Zaman, 2019](#)) and anxiety disorder ([Cui et al., 2019](#); [Rodrigues et al., 2019](#)).

As research on neuromodulation of non-pharmaceutical treatment for schizophrenia continues to expand, a bibliometric analysis of these studies could provide valuable insights into the recent trends and directions of neuromodulation schizophrenia research. This is done so that future researchers can consider specific areas of neuromodulation-schizophrenia research that can be investigated further, laying the groundwork for the use of neuromodulation techniques in the treatment of schizophrenia.

To gain insights into the current global trajectory of neuromodulation schizophrenia research, we conducted a comprehensive bibliometric analysis of relevant literature published from 2019 to 2023. The bibliometric analysis focused on publications employing neuromodulation devices such as EEG, MEG and fMRI neurofeedback, DBS, TMS, repetitive transcranial magnetic stimulation (rTMS), tDCS, transcranial focused ultrasound stimulation (tFUS), and transcranial alternating current stimulation (tACS). To our knowledge, no bibliometric studies have been undertaken to examine the landscape of neuromodulation-schizophrenia research comprehensively. Consequently, there is no comprehensive overview of neuromodulation-schizophrenia publications and the trends in this field over the past five years.

Furthermore, the quantitative bibliometrics analysis provides data on neuromodulation-schizophrenia advancement and research area hotspots, research collaboration, and cutting-edge neuromodulation-schizophrenia research trends that could benefit future researchers. This bibliometric paper explored publications from the Scopus database, specifically on neuromodulation-schizophrenia research in the past five years, starting from 2019 to 2023, to provide answers to the following research questions (RQ): (1) What are the most-cited articles and the most common keywords in the neuromodulation-schizophrenia research domain between 2019 and 2023? (2) What are the most productive countries, institutions and authors in the neuromodulation-schizophrenia research domain between 2019 and 2023, as Total Publications (TP) reported? (3) What are the main findings and protocols of the selected studies that employed neuromodulation techniques in the last five years (2019 – 2023)?

2.0 METHODOLOGY

Data collection was carried out in November 2023 from the Scopus database. Elsevier introduced the Scopus database in 2004, and has since established itself as a comprehensive and well-known bibliographic data source ([Pranckutė, 2021](#)). This comprehensive resource encompasses over 25,000 journals from around the globe, representing over 7,000 publishers, and offers extensive coverage of scientific, technical, medical, and social science disciplines ([Elsevier, 2023](#); [Pranckutė, 2021](#)). Additionally, it provides comprehensive citation data, such as the number of times an article has been cited, as well as a range of measures, such as the h-index and Scimago Journal Rank (SJR), to assess the impact of research ([Harzing & Alakangas, 2015](#)).

Data was collected from the Scopus database from 2019 to 2023. All data published in the Scopus database during data collection was included. However, bibliometric data from December 2023 was not included in this data. **Figure 1** illustrates the flow of the search strategy. Keywords such as "schizophrenia," "schizophrenic," "transcranial magnetic stimulation," "transcranial direct current stimulation," "transcranial alternating current stimulation," "deep brain stimulation," "transcranial focused ultrasound stimulation," "neurofeedback," and Boolean operators such as "AND" and "OR" were used for databases searching. The selected keywords reflected neuromodulation methods employed in both research and treatment of schizophrenia. The query was as follows:

((TITLE-ABS-KEY(schizophrenia OR schizophrenic) AND TITLE-ABS-KEY("transcranial magnetic stimulation" OR TMS OR "transcranial direct current stimulation" OR tdcS OR "transcranial alternating current stimulation" OR "transcranial focused ultrasound stimulation" OR FUS OR "deep brain stimulation" or neurofeedback))

Eight hundred eighty-five (885) articles were retrieved. Then, the titles and abstracts of the articles were reviewed. Finally, three hundred fifty-three (353) articles were chosen that met the research criteria. The co-occurrence of words or terms in the data corpus, specifically from the titles and abstracts, was used for the bibliometric analysis. VOSviewer was used to analyze the citation data, alongside Harzing's Publish or Perish (PoP) and Microsoft® Excel for data cross-checking purposes.

To answer RQ1 and RQ2, bibliometric analysis was used to understand the global trends in neuromodulation schizophrenia research from 2019 to 2023. Bibliometric analysis provides information such as the most productive journals, authors, countries, academics/institutions, and the most-cited articles on relevant topics based on the publication outputs from 2019 to 2023.

Limiting the analysis to 2019 to 2023 ensures that the data is current and reflects the rapidly evolving trends and advancements in neuromodulation-schizophrenia research. As a result, a focus on the most recent research findings, methodologies, and technologies in this domain is possible.

To answer RQ3, 20 articles published in the field of neuromodulation-schizophrenia research between 2019 to 2023 were selected and presented in **Table 1**. The selection of the 20 articles was based on their relevance to the research goals. A variety of neuromodulation methods used in schizophrenia research and treatment were included. Additionally, articles with full-text availability were chosen to ensure accessibility. The aim was to provide a comprehensive overview while maintaining inclusivity and reliability. As depicted in **Figure 1**, 353 publications were included in the bibliometric analysis to answer RQ1 and RQ2. From 353 documents, and after reviewing full-text documents, 20 articles were selected to answer RQ3 (**Table 1**).

Table 1. Summary of the selected journal articles (2019 – 2023) to identify the neuromodulation methods, main findings, and protocol of the studies.

No.	First Author & year	Brain areas target & number of subjects	Methods (Device)	Neuromodulation protocol	Main findings
1	Zhou et al. (2023)	• Left DLPFC, contralateral upper orbital border area • 38 chronic schizophrenia patients (21 active; 17 sham group)	tDCS	• 2 mA • 15 consecutive session • Sham and tDCS	No significant differences in cognitive and neuropsychological performance between active and sham tDCS groups
2	Wang et al. (2023)	• Left DLPFC • 76 schizophrenia patients (48 active; 28 sham group)	rTMS	• 10Hz • 5 times a week for 1 month	Schizophrenia patients with the TT genotype had poorer cognitive performance than C allele carriers. COX-2 rs5275 was associated with improved immediate memory in SCZ patients after rTMS treatment
3	Zhai et al. (2023)	• Left DLPFC • 26 schizophrenia patients (13 active; 13 sham group)	TUS	• 3.8 focal length, 500 kHz fundamental frequency • 15 sessions	Alleviate the negative symptoms of schizophrenia patients and enhance the cognitive performance
4	Biačková et al. (2024)	• Left premotor cortex • 16 early-course schizophrenia patients, 16 healthy controls	TMS-EEG	• Intensity stimulation is set at 120% of the RMT, biphasic single-pulses	A significant reduction in the natural frequency of patients with early-course schizophrenia patients compared to healthy individuals
5	Zhang et al. (2022)	• DLPFC & TPJ • 25 schizophrenia or schizoaffective patients (14 active; 11 sham group)	tACS and EEG	• 10 Hz alternating current • 5 days (40 min/day)	tACS treatment successfully engaged the treatment target by increasing alpha power. Successful target engagement reduced depression and other general psychopathology symptoms, but not auditory hallucinations in schizophrenia patients
6	Bidzinski et al. (2022)	• DLPFC • 19 schizophrenia patients (9 active; 10 sham group)	rTMS	• 20 Hz • 5 times per week (4 weeks)	Active rTMS also improved attention and suppressed increased tobacco use that was associated with cannabis reductions
7	Nestoros and Vallianatou (2022)	• Right and left hemispheres • 1 male schizophrenia patient	EEG-Neurofeedback	• Infra-low frequency • 1 hr per session	The patient reported having infrequent and manageable auditory hallucinations that were only triggered by stress after the NF session
8	Moeller et al. (2022)	• Insula, prefrontal cortex • 20 schizophrenia patients (10 active; 10 sham group)	Deep rTMS	• 10 Hz • 20 mins, every weekday (3 weeks)	Insula-inclusive deep rTMS reduced motivation to smoke during withdrawal and modulated insula-centric neural function in schizophrenia patients

9	Markiewicz et al. (2021)	• Right and left hemispheres • 44 schizophrenia patients (22 standard rehabilitation; 22 NF group)	EEG-Neurofeedback	• NF training sessions were held twice a week for three months • GSR method was used	Neurofeedback enhanced self-efficacy and BDNF serum levels in the NF group
10	Chang et al. (2021)	• Frontoparietal region • 36 schizophrenia patients (18 active; 18 sham group)	tACS	• 6 Hz, 2 mA • Twice daily, 20 min per session	tACS showed efficacies for negative symptoms, cognitive symptoms, WM capacity, and psychosocial functions
11	Bation et al. (2021)	• Left DLPFC • 22 schizophrenia patients (12 active, 10 sham)	iTBS-rTMS and fMRI	• 5 Hz, 3 pulses for 2s • 20 sessions (2 sessions per workday for 2 weeks)	The active group showed decreased negative symptoms and increased brain functional connectivity between left DLPFC and right lateral occipital cortex, angular gyrus, and midbrain
12	Cascella et al. (2021)	• Bilateral substantia nigra • 1 female schizophrenia patient	DBS	• 1.0 V and 0.8 V • Monopolar stimulation, pulse width 60 ms, frequency • 130 Hz	The patient phonemic and semantic fluency improved markedly; chronic hallucinations resolved immediately and completely
13	Boudewyn et al. (2020)	• Left DLPFC • 27 schizophrenia patients	tDCS and EEG	• 2 mA for 20 min with a 30-s ramp-up and ramp-down (Active) • Current ramped down and remained off after the 30-s ramp-up at the beginning of the 20 min (Sham)	Increased in EEG gamma power that was indicative of enhanced proactive cognitive control.
14	Guan et al. (2020)	• Left DLPFC • 56 schizophrenia patients (28 active; 28 sham)	rTMS	• 20 Hz • 40 sessions, 5 times a week for 8 weeks	Significantly increased the immediate memory score in the active group
15	Walther et al. (2020)	• Left IFG, right IPL, left IPL • 20 schizophrenia patients, 20 healthy controls	rTMS	• iTBS > left IFG • cTBS, 30 Hz > right IPL • placebo > left IPL • Single session each	Single sessions of cTBS on the right IPL improved both gesture performance accuracy and manual dexterity
16	Amico et al. (2022)	• Whole brain • 4 schizophrenia patients	EEG-Neurofeedback	• LORETA Z-score NFT	Elevated frontal, central, and temporal theta absolute power normalized after treatment
17	Zhuo et al. (2019)	• Left DLPFC • 60 schizophrenia patients (33 active; 27 sham group)	rTMS	• 20 Hz • 20 treatment sessions, 5 times a week for 4 weeks	There was a significant decrease in negative symptoms but no cognitive improvement

18	Yoon et al. (2019)	• Left DLPFC, left TPJ • 7 schizophrenia patients	tDCS and fMRI	• 2 mA, 20 min per session • Twice daily for 5 days	tDCS boosted functional network connectivity, leading to reduced hallucinations
19	Schülke and Straube (2019)	• Frontal, parietal, frontoparietal • 20 schizophrenia patients, 29 healthy controls	tDCS	• 1.5 mA • LFC-RFA, LFC-RPA, LPC-RPA, sham • Single session each	Left frontal tDCS can improve semantic co-verbal gesture processing in schizophrenia patients
20	Pazooki et al. (2019)	• Whole brain • 2 schizophrenia patients (male & female)	EEG-neurofeedback	• NF training session was done in 4 phases	NF training improved social, interpersonal, and cognitive abilities, hence reducing the negative symptoms

BDNF: Brain-derived neurotrophic factor; **COX:** Cyclooxygenases; **ctBS:** Continuous theta burst stimulation; **DBS:** Deep brain stimulation; **DLPFC:** Dorsolateral prefrontal cortex; **EEG:** Electroencephalography; **fMRI:** Functional magnetic resonance imaging; **GSR:** Galvanic skin response; **Hr:** Hour; **Hz:** Hertz; **IFG:** Inferior frontal gyrus; **IPL:** Inferior parietal lobe; **itBS:** Intermittent theta burst stimulation; **LFC-RFA:** Left frontal cathodal-Right frontal anodal; **LFC-RPA:** Left frontal cathodal-Right parietal anodal; **LPC-RPA:** Left parietal cathodal-Right parietal anodal; **mA:** Milliampere; **Min:** Minute; **ms:** Millisecond; **NF:** Neurofeedback; **NFT:** Neurofeedback training; **tDCS:** Transcranial direct current stimulation; **RMT:** Resting motor threshold; **rTMS:** Repetitive transcranial magnetic stimulation; **s:** Second; **SCZ:** schizophrenia; **tACS:** Transcranial alternating current stimulation; **TMS:** Transcranial magnetic stimulation; **TPJ:** Temporoparietal junction; **TUS:** Transcranial ultrasound stimulation; **V:** Voltage; **WM:** Working memory.

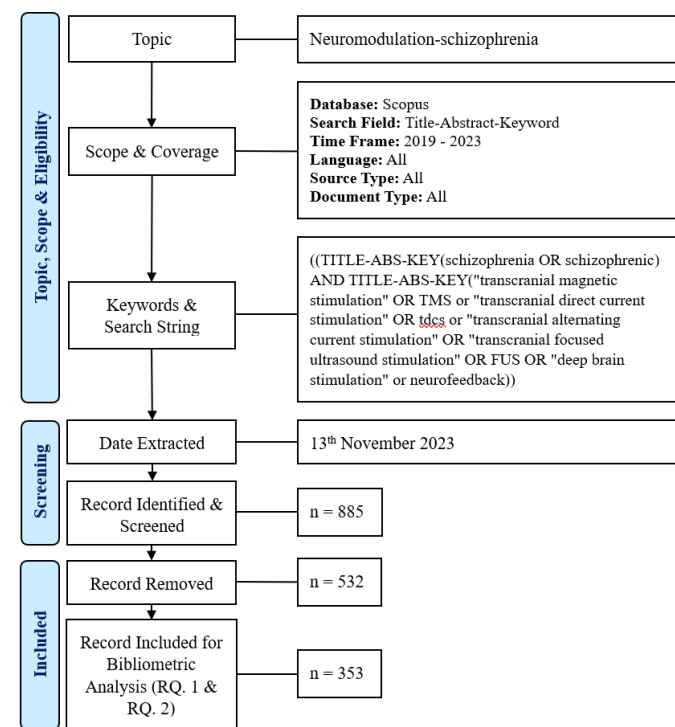


Figure 1. Flow diagram of the search strategy

3.0 RESULTS

3.1 Bibliometric analysis

The number of documents, type of document and source type

We reviewed and analyzed 353 documents related to neuromodulation-schizophrenia research from the Scopus database. The year 2022 had the highest number of publications, with 87 articles published. Meanwhile, 2019 had the least publications, with 57, as shown in **Figure 2** and 2021 had the highest number of citations, with 960 citations.

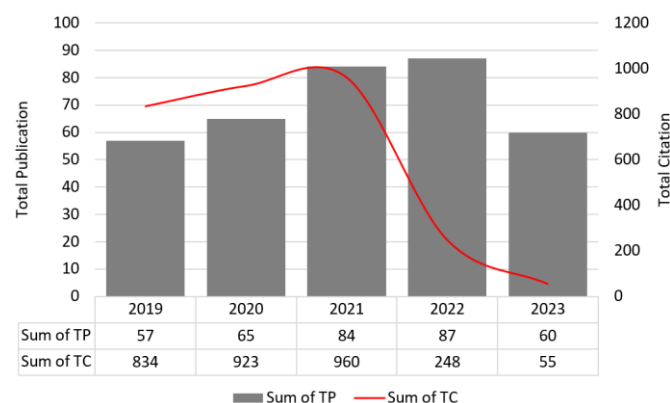


Figure 2. The number of publications and citations in the neuromodulation-schizophrenia research.

Table 2 shows that more than half (number of publication = 218, 61.76%) of the documents published in this area of research were research articles, followed by review articles (87, 37.05%), letters (29, 8.22%), and book chapters (7, 1.98%). Meanwhile, **Table 3** shows that most of the documents were published in journals with 342 publications.

Table 2. Types of documents.

Document type	Number of documents	Percentage
Article	218	61.76
Review	87	24.65
Conference Paper	3	0.85
Book chapter	7	1.98
Note	3	0.85
Letter	29	8.22
Erratum	2	0.57
Book	1	0.28
Editorial	3	0.85
Total	353	100.00

Table 3. Source types.

Source Type	Total Publications (TP)	Percentage
Journal	342	96.88
Book	7	1.98
Book Series	1	0.28
Conference Proceeding	3	0.85
Total	353	100.00

Leading countries and institutions

Forty-seven (47) countries contributed to the publication of neuromodulation schizophrenia research from 2019 – 2023. This global contribution shows diverse perspectives on using neuromodulation techniques in treating schizophrenia. From the network analysis, 19 countries published more than 5 publications and collaborated in 2019 – 2023 (**Figure 3**). The network visualization of countries in **Figure 3** is interpreted by observing the line thickness connecting the countries. The stronger the scientific collaboration, the thicker the line link between the countries. International collaboration in neuromodulation-schizophrenia research, visualized in **Figure 3** showed the highest strength of collaboration between the countries of the USA, Canada and China.

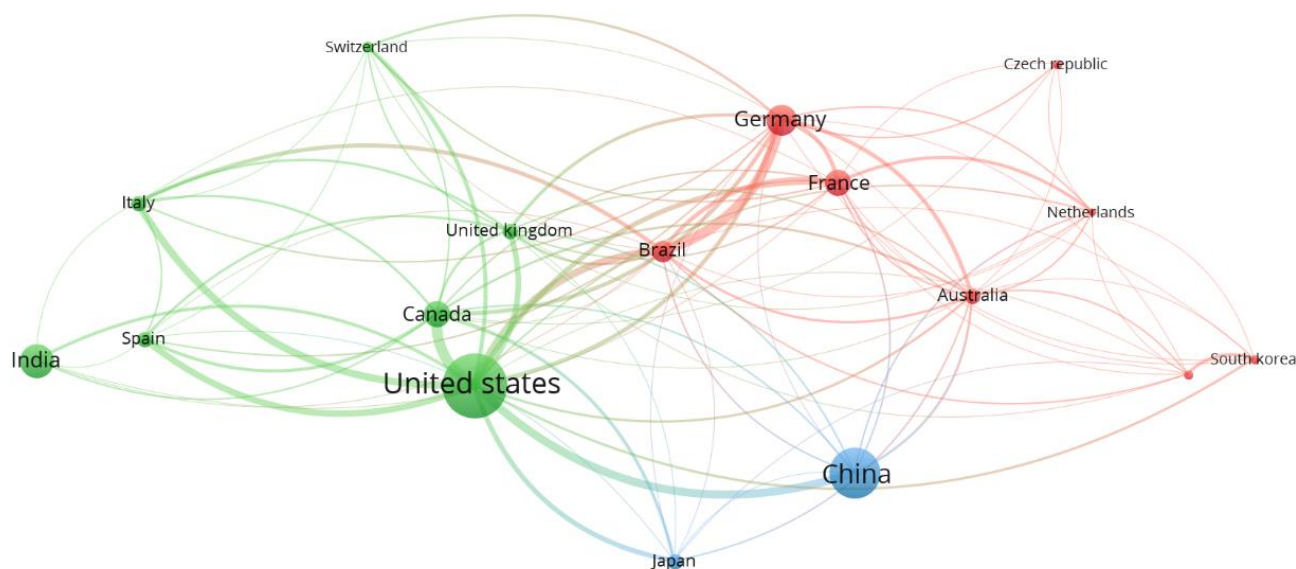


Figure 3. Network visualization of countries (minimum of 5 publications)

Table 4. The 10 most productive countries and institutions in neuromodulation-schizophrenia research.

No.	Country	TP	TC	The most productive institution	TPI	TCi
1	United States	96	1249	Harvard Medical School	14	147
2	China	71	442	Shanghai Jiao Tong University	16	133
3	India	43	426	National Institute of Mental Health and Neuro Sciences	28	371
4	Germany	39	383	Klinikum der Universität München	17	143
5	Canada	32	420	University of Toronto	17	265
6	France	31	327	Centre de Recherche en Neurosciences de Lyon	20	274
7	Brazil	24	397	Universidade de São Paulo	16	346
8	Japan	17	230	National Center of Neurology and Psychiatry	9	107
9	Australia	16	144	UNSW Sydney	4	23
10	Italy	16	381	Università degli Studi di Padova	4	81

TP: Total publications; **TC:** Total citations; **TPI:** Total publication by institutions; **TCi:** Total citations by institution.

The top 10 countries that contributed to the most publications are listed in **Table 4**. It shows that the United States published the highest number of publications with the most highly cited documents in this study (Total Publication (TP), 96; Total Citation (TC), 1249). Hence, it is a key player in neuromodulation-schizophrenia research. Fourteen of the publications were published by Harvard Medical School. China is the second most productive country with 71 publications (TC, 442), followed by India, Germany, and Canada with 43 (TC, 426), 39 (TC, 383) and 32 (TC, 420) publications respectively. In sixth, seventh and eighth place are France (TP, 31; TC, 327), Brazil (TP, 24; TC, 397) and Japan (TP, 17; TC, 230). Meanwhile, Australia and Italy had the least publications, with 16 publications each. From the 16 publications, Italy had much higher citations (TC, 381) than Australia, with 144 total citations.

The National Institute of Mental Health and Neurosciences (NIMHANS) in India is the most productive institution, with 28 publications and the highest cited with 371. Centre de Recherche en Neurosciences de Lyon in France is the second-most-productive academic institution in this study, with 20 publications. Klinikum der Universität München and University of Toronto follow with 17 publications each. Shanghai Jiao Tong University in China and Universidade de São Paulo in Brazil published 16 publications. The National Center of Neurology and Psychiatry in Japan published 9 publications. Finally, UNSW Sydney and Università degli Studi di Padova published 4 publications each. UNSW Sydney had the least cited publications with 23 total citations.

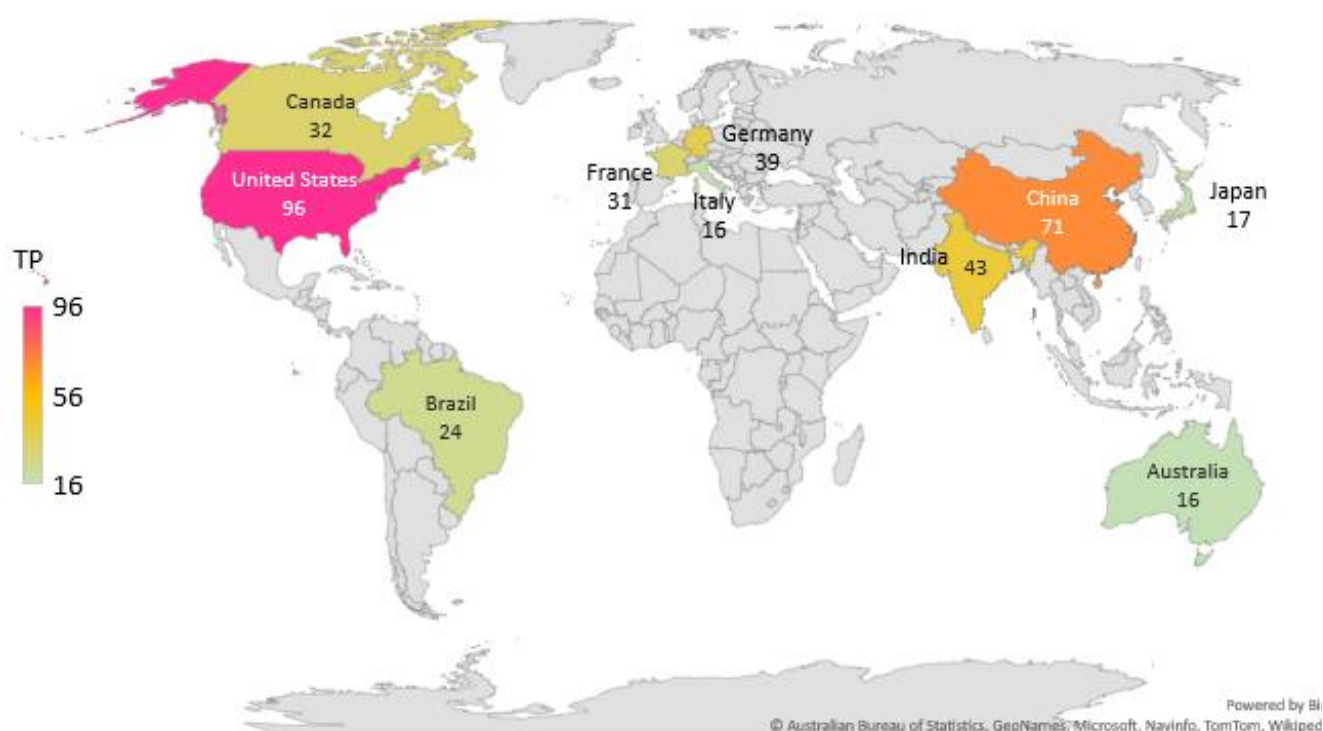


Figure 4. The geographical distribution of publications.

Table 5. The 10 most productive authors in the neuromodulation-schizophrenia research topic.

No.	Author's name	TP	TC	h-index	Affiliation	Country
1	Brunelin, J.	19	274	38	Université Lyon 1	France
2	Venkatasubramanian, G.	15	266	30	National Institute of Mental Health And Neurosciences (NIMHANS)	India
3	Brunoni, A.R.	14	332	63	Universidade de São Paulo	Brazil
4	Sreeraj, V.S.	12	68	11	National Institute of Mental Health And Neurosciences (NIMHANS)	India
5	Mehta, U.M.	11	84	17	National Institute of Mental Health And Neurosciences (NIMHANS)	India
6	Mondino, M.	11	55	21	Université Lyon 1	France
7	Wang, H.	11	34	35	Fourth Military Medical University,	China
8	Blumberger, D.M.	10	163	44	University of Toronto	Canada
9	Sivakumar, V.	10	65	22	National Institute of Mental Health And Neurosciences (NIMHANS)	India
10	Hasan, A.	10	59	46	University of Augsburg	Germany

TP: Total publications; TC: Total citations.

Figure 4 shows the geographical distribution of publications. The United States and Canada resided in the North American continent. Three countries, China, India and Japan, are situated in the Asia continent. Germany, Brazil and Australia represented the Europe, South America and Oceania continent, respectively.

Leading authors

The productivity of individual authors in neuromodulation-schizophrenia research was measured by counting the total number of publications each author produced during the study period

(2019 – 2023). As shown in **Table 5**, the top ten most productive authors in neuromodulation schizophrenia research were from only France, India, Brazil, China, Canada, and Germany.

The author with the most publications on the topic is Brunelin, J., who has published 19 publications, has an h-index of 38 and has been cited 274 times. The author is affiliated with Université Lyon 1 of France. Dr. Brunelin has 20 years of experience in leading to significant contributions to knowledge and practice on the use of neuromodulation techniques in treating

neuropsychiatric disorders, particularly schizophrenia. He is also affiliated with the European Society for Brain Stimulation. The second, third and fourth most productive authors on the list are Venkatasubramanian, G. (15 publications, 266 citations), Brunoni, A.R. (14 publications, 332 citations), Sreeraj, V.S. (12 publications, 68 citations) with Brunoni, A.R. having the highest total citations of 332 among all of the authors. Mehta, U.M., Mondino, M., and Wang, H. have each published eleven publications. Blumberger, D.M., Sivakumar, V. and Hasan, A. from Canada, India and Germany, respectively, have each published ten publications.

Journal outcomes

The ten most productive journals in neuromodulation-schizophrenia research are shown in **Table 6**. The Schizophrenia Research published the most documents, with 27 publications over 2019 – 2023, with a total citation of 259. The most cited article from the 27 publications was from Kostova and colleagues (2020) entitled "Targeting cognition in schizophrenia through transcranial direct current stimulation: A systematic review and perspective". Meanwhile, the Journal of Electroconvulsive Therapy (ECT) published the least documents, with 5 publications and a total of 29 citations. The least cited journal is the journal Trials, which has a total of 18 citations from 7 publications. According to Scopus, it also has the lowest Cite Score, which is 3.6 for the cumulative year.

Leading citations

Citation analysis was used to understand the formation, scope, and direction of research streams in neuromodulation-schizophrenia research. Citation analysis is a bibliometric method that counts the number of times other publications cite a specific article to assess its reputation and impact in a specific field of scientific research (Kumar et al., 2020). We used this method to identify the top 10 most influential articles in neuromodulation-schizophrenia research based on total citations per year (TC), as shown in **Table 7**. The number of times an article has been cited by other papers in the Scopus database is represented by TC (Ahmi, 2022).

The most cited document was published by Fregni and colleagues in 2021 and is titled "Evidence-based guidelines and secondary meta-analysis for the use of transcranial direct current stimulation in neurological and psychiatric disorders." It was published by the International Journal of Neuropsychopharmacology and has been cited 197 times. With 40 citations, documents

published by Corripio and colleagues (2020) and Chen and colleagues (2019) are the least cited documents among the top 10 articles, as shown in **Table 7**. The documents are titled "Deep brain stimulation in treatment-resistant schizophrenia: A pilot randomized cross-over clinical trial" and "Neural correlates of auditory verbal hallucinations in schizophrenia and the therapeutic response to theta-burst transcranial magnetic stimulation," respectively.

Keyword analysis

Keyword analysis is an effective quantitative method for exploring specific topics in neuromodulation schizophrenia research and identifying emerging trends. This approach rests on the premise that keywords provide a reliable reflection of the core contents conveyed in the publications in which they are utilized. This approach has been widely used in recent years (Alsharif et al., 2021; Wang & Chai, 2018).

A numerical number representing the association between two terms represents the link; the greater the value, the stronger the correlation (Ahmi, 2022; Goyal & Kumar, 2020). The number of times two keywords appear together in the same article is represented by the link strength between them, and the total number of these links refers to the total number of times these two keywords appear together.

The minimum number of occurrences of a keyword in the VOSviewer for it to be displayed was set at ten for the current study. This indicates that a keyword will appear on the bibliometric map if it appears in a document with another term more than 10 times. The keyword co-occurrence analysis in this study used 2341 keywords from 353 articles. The keywords were inserted into VOSviewer to create a map of the literature with a minimum of ten occurrences, and 75 keywords met this threshold, as shown in **Figure 5**.

The network analysis map shows three clusters of keyword occurrences in neuromodulation-schizophrenia research. Five (5) clusters are represented in different colors. Cluster 1 (red) shows the relationship between cognition, behavior and psychological state. Cluster 2 (green) shows the brain regions that are being stimulated and studied. Cluster 3 (blue) shows the relationship between treatment duration and response toward neuromodulation. The neuromodulation and brain stimulation devices are represented in Cluster 4 (mustard-yellow). Lastly, Cluster 5 (purple) represents the relationship between the neuron excitability and the brain stimulation device.

Table 6. The 10 most productive journals in the neuromodulation-schizophrenia research topic.

No.	Journal	TP	TC	Cite Score 2022	The most cited articles	Time cited	Publisher
1	Schizophrenia Research	27	259	7.4	Targeting cognition in schizophrenia through transcranial direct current stimulation: A systematic review and perspective	30	Elsevier BV
2	Psychiatry Research	24	178	13.4	Real-time fMRI neurofeedback reduces auditory hallucinations and modulates resting state connectivity of involved brain regions: Part 2: Default mode network -preliminary evidence	27	Elsevier Ireland Ltd
3	Frontiers in Psychiatry	22	112	5.4	Effects of high-frequency transcranial magnetic stimulation for cognitive deficit in schizophrenia: A meta-analysis	39	Frontiers Media SA
4	Journal of Psychiatric Research	14	96	6.0	A meta-analysis of transcranial direct current stimulation for schizophrenia: "Is more better?"	38	Elsevier Ltd
5	Brain Stimulation	13	154	12.9	Transcranial direct-current stimulation in ultra-treatment-resistant schizophrenia	46	Elsevier Inc
6	Asian Journal of Psychiatry	11	73	10.9	High definition transcranial direct current stimulation (HD-tDCS): A systematic review on the treatment of neuropsychiatric disorders	20	Elsevier BV
7	Schizophrenia Bulletin	10	137	11.5	Neural correlates of auditory verbal hallucinations in schizophrenia and the therapeutic response to theta-burst transcranial magnetic stimulation	40	Oxford University Press
8	Trials	7	18	3.6	Structural and functional brain biomarkers of clinical response to rTMS of medication-resistant auditory hallucinations in schizophrenia patients: Study protocol for a randomized sham-controlled double-blind clinical trial	6	BioMed Central Ltd
9	Frontiers in Neuroscience	6	68	6.8	Systemic review on transcranial electrical stimulation parameters and EEG/fNIRS features for brain diseases	38	Frontiers Media SA
10	Journal of Electroconvulsive Therapy (ECT)	5	29	3.9	Online theta frequency transcranial alternating current stimulation for cognitive remediation in schizophrenia: A case report and review of literature	14	Lippincott Williams and Wilkins

TP: Total publications; **TC:** Total citations.

Table 7. Top 10 articles on the Scopus database ordered by citation score.

No.	First Author & Year	Title	Journal	Publisher	TC 2023
1	Fregni et al. (2021)	Evidence-based guidelines and secondary meta-analysis for the use of transcranial direct current stimulation in neurological and psychiatric disorders	International Journal of Neuropsychopharmacology	Oxford University Press	197
2	Chase et al. (2020)	Transcranial direct current stimulation: a roadmap for research, from mechanism of action to clinical implementation	Molecular Psychiatry	Springer Nature	103

3	Begemann et al. (2020)	Efficacy of non-invasive brain stimulation on cognitive functioning in brain disorders: A meta-analysis	Psychological Medicine	Cambridge University Press	89
4	Ahn et al. (2019)	Targeting reduced neural oscillations in patients with schizophrenia by transcranial alternating current stimulation	NeuroImage	Academic Press Inc.	82
5	Valiengo et al. (2020)	Efficacy and safety of transcranial direct current stimulation for treating negative symptoms in schizophrenia: A randomized clinical trial	JAMA Psychiatry	American Medical Association	61
6	Correll et al. (2021)	Efficacy and acceptability of pharmacological, psychosocial, and brain stimulation interventions in children and adolescents with mental disorders: An umbrella review	World Psychiatry	John Wiley and Sons Inc	57
7	Limori et al. (2019)	Effectiveness of the prefrontal repetitive transcranial magnetic stimulation on cognitive profiles in depression, schizophrenia, and Alzheimer's disease: A systematic review	Progress in Neuro-Psychopharmacology and Biological Psychiatry	Elsevier Inc.	54
8	Lindenmayer et al. (2019)	Transcranial direct-current stimulation in ultra-treatment-resistant schizophrenia	Brain Stimulation	Elsevier Inc.	46
9	Corripio et al. (2020)	Deep brain stimulation in treatment-resistant schizophrenia: A pilot randomized cross-over clinical trial	EBioMedicine	Elsevier B.V.	40
10	Chen et al. (2019)	Neural correlates of auditory verbal hallucinations in schizophrenia and the therapeutic response to theta-burst transcranial magnetic stimulation	Schizophrenia Bulletin	Oxford University Press	40

TC: Total citations.

Figure 6 shows a density visualization of keyword occurrences. **Table 8** summarises the most occurrences of keywords in the Scopus database in the neuromodulation-schizophrenia research.

"Schizophrenia" and "human" charted the topmost occurrence of the keyword, as shown in **Table 8**. In addition, "transcranial direct current stimulation," "transcranial magnetic stimulation," and "repetitive transcranial magnetic stimulation" are the topmost neuromodulation devices that are examined concerning neuromodulation-schizophrenia research. Further, "cognition," "treatment outcome," "dorsolateral prefrontal cortex," and "auditory hallucination" were also observed to be highly associated with neuromodulation-schizophrenia research. "Electroencephalography" and "cognitive dysfunction" also had a strong association with neuromodulation-schizophrenia research (77 occurrences, 754 total link strength and 60 occurrences, 704 total link strength, respectively).

3.2 Summary of the selected journal articles

Table 1 summarises the selected journal articles in neuromodulation-schizophrenia research for the year 2019 to 2023. The summary acknowledges the main findings of each study, as well as their neuromodulation protocol.

4.0 DISCUSSION

This review provides an overview of the neuromodulation-schizophrenia studies between 2019 to 2023. The study revealed a clear interest in neuromodulation-schizophrenia studies from 2019 to 2023, with tDCS, TMS and rTMS being the most common neuromodulation devices based on the increased keyword occurrences used (**Table 8**). These non-invasive brain stimulation devices are in demand, particularly among drug-resistant schizophrenia patients. Physicians are finding ways for patients to use non-pharmaceutical therapy, and brain stimulations are one of the ways.

Research has shown these brain stimulations can modulate schizophrenia symptoms, such as reducing auditory hallucinations, enhancing working memory, improving depressive symptoms, and decreasing social withdrawal ([Dokucu, 2015](#); [Wu et al., 2022](#)). The brain stimulation devices targeted certain brain areas responsible for cognitive function, such as the dorsolateral prefrontal cortex (DLPFC). DLPFC is the key node in the central executive function, including working memory and selective attention ([Bonotis et al., 2022](#); [Curtis & D'Esposito, 2003](#)), and has remained the gold standard of stimulation for neuropsychiatric disorders. **Table 8** also shows that DLPFC is one of the top keywords in neuromodulation-schizophrenia research from 2019 to 2023.

Table 8. Top keywords by the frequency of their occurrence.

Keywords	Occurrence / Frequency	Total link strength
Schizophrenia	332	2973
Human	315	2976
Transcranial direct current stimulation	159	1504
Transcranial magnetic stimulation	151	1446
Repetitive transcranial magnetic stimulation	114	1119
Positive and negative syndrome scale	109	1196
Cognition	89	984
Treatment outcome	88	936
Dorsolateral prefrontal cortex	87	971
Auditory hallucination	85	876
Electroencephalography	77	754
Cognitive dysfunction	60	704

Also, the most productive country in neuromodulation-schizophrenia research is the United States. The United States has been at the forefront of using neuromodulation techniques in treating neuropsychiatric disorders. Prefrontal TMS therapy was approved by the US Food and Drug Administration (USFDA) in 2008 for the treatment of major depressive disorder (MDD) in patients resistant to medications ([Rizvi & Khan, 2019](#)). They also expanded the usage in 2013 to include TMS for treating migraine-associated pain and later in 2018 to also permit the usage of TMS for treatment of obsessive-compulsive disorder (OCD) ([U. S. Food And Drug Administration, 2018](#)). As shown by the number of publications in the neuromodulation-schizophrenia research by the USA, they are en route to

exploring the usage of neuromodulation techniques for schizophrenia in the near future.

The summary of the selected journal articles in **Table 1** highlights positive findings in neuromodulation research in alleviating schizophrenia symptoms. Notably, the novel and innovative neuromodulation technique, the focused ultrasound (FUS), has only been explored in studies conducted in 2023. Recent investigations, both in humans ([Zhai et al., 2023](#)) and rats ([Pan et al., 2023](#)), have demonstrated its efficacy in treating schizophrenia. This novel technology directs ultrasound energy beams with precision onto deep brain targets, eliciting neuromodulated therapeutic effects without causing damage to surrounding normal tissue. This paves the way for future research into the application of focused ultrasound in the treatment of schizophrenia, in conjunction with well-established neuromodulation techniques such as rTMS and tDCS. Consequently, it establishes a foundation for incorporating neuromodulation in the treatment of schizophrenia, especially for drug-resistant schizophrenia patients.

The utilization of neuromodulation in schizophrenia treatment has demonstrated a beneficial trend, serving as a complementary approach alongside antipsychotic drugs. Given the documented adverse effects associated with prolonged antipsychotic drug use ([Chiliza et al., 2015](#); [Uludag et al., 2021](#)), it is crucial to ensure the availability and accessibility of neuromodulation techniques for patients.

In addition, forthcoming studies can explore the incorporation of machine learning-based predictive models, specifically examining the treatment of schizophrenia. These models, such as the antipsychotic-based ones proposed by Uludag and colleagues ([2023](#)), can be utilized and supported to augment bibliographic investigations.

There are a few limitations in this study. First, we limited our bibliometric study to the Scopus database. Although the Scopus database is reputable, we may incorporate and combine other databases in future studies, such as Web of Science or Google Scholar, to capture studies not covered in this paper and provide more extensive insights. Second, we employed bibliometric approaches to evaluate the database metadata. Bibliometric approaches offer the advantage of providing quantitative metadata analysis. On the other hand, the study of publication content is limited to article keywords rather than article content. Further research

could employ a method such as a systematic literature review to investigate the article's content more qualitatively and in-depth. Nonetheless, we were able to summarize the essential findings and neuromodulation protocols of some of the selected journal articles from 2019 to 2023 to identify trends and gaps in neuromodulation-schizophrenia research.

5.0 CONCLUSION

The neuromodulation technique is viewed as a potential neurotherapy for schizophrenia, as evidenced by the increased interest from researchers around the world. Of note is that the geographical distribution of the research includes not only the Americas continent but also the Asia continent, suggesting the growth of the usage of neuromodulation techniques worldwide in schizophrenia treatment. Despite its limitations, this

bibliometric study can be useful for future research trends as it provides a comprehensive analysis of neuromodulation-schizophrenia research, which may be helpful for clinicians and researchers in delivering neuromodulation techniques, particularly for drug-resistant schizophrenia patients.

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